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MODELS OF CLOSED-LOOP USE/REPAIR CYCLES
WITH APPLICATION TO THE DD-963 MAIN PRO-
PULSION ENGINES

Samuel Stephenson Montgomery, et al

Naval Postgraduate School
Monterey, California

September 1972

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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WITH APPLICATION TO
THE DD-963 MAIN PROPULSION ENGINES

by

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and

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13. ABSTRACT

This thesis describes and compares two models which may be used as tools in making logistic support decisions for closed-loop systems, such as the use/repair cycle of the LM-2500 gas turbine engines. The models are then used to study the effect of changes in various system parameters. The models are a computer simulation developed by Cushing, Gautier, and Long [1] and an analytical model developed by Koenigsberg [2].

The steady-state behavior of both models is essentially the same, with the analytical model consistently more conservative than the simulation model.

The analytical model has been adapted to a time-shared interactive computer system which allows the policy planner to immediately obtain effects on the system of changes in any one of seven parameters.

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II

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Models of Closed-Loop Use/Repair Cycles
With Application to
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I. INTRODUCTION

Litton Industries has been awarded a contract to build
30 SPRUANCE Class destroyers for the United States Navy with
first delivery scheduled for December 1974. Each ship will
be equipped with four General Electric LM-2500 gas turbine
engines for main propulsion. The present maintenance plan
provides for an age replacement policy, i.e., each engine
will be removed upon attaining some prescribed number of
operating hours or upon failure, whichever occurs first.
Upon removal, the engine will be replaced by a ready-for-
issue (RFI) engine obtained from an RFI pool and the removed
engine sent to a central repair facility for repair and
return to the RFI state, thus forming a closed-loop use/-
repair system. The number of spare engines to buy, and the
repair capability to establish, are to be determined.

This thesis describes and compares two models which may
be used as tools in making logistic support decisions for
closed-loop systems, such as the use/repair cycle of the
LM-2500 gas turbine engines. The models are then used to
study the effect of changes in various system parameters.
The models are a computer simulation developed by Cushing,
Gautier, and Long [1] and an analytical model developed by
Koenigsberg [2].

The main decision variables are the pool size, number of
repair lines, time to repair, and the ratio of time-between-
overhaul (TBO) to annual hours per engine (TOR).

With TBO = 4,000 hours, TOR = 2,000 annual hours per engine, pool size = 19, repair time = 5 weeks, number of repair lines = 6, as the base case for analysis, the parameters were varied through ranges above and below their base case values. The results consistently reveal that the pool size can vary over a wide range, from a minimum of 12, with little or no effect on the status of the operating fleet. However, the status of the fleet is extremely sensitive to the other parameters, especially the number of repair lines, repair time, and TBO. For example, if all parameters except TBO are kept at base case values, and TBO is increased from 4,000 to 6,000 hours, the average number of engines short in the fleet drops from about 10 to virtually zero.

Both models give essentially the same steady-state results with the analytical model requiring much less computer time. This makes possible the use of the analytical model in a real time interactive computer system. However, the simulation model provides the flexibility to handle a larger range of problems such as those with transportation delays. Because of the long running time and other inherent characteristics of the simulation model, it cannot be used in a real time mode.

The analytical model has been adapted to a time-shared interactive computer system which allows the policy planner to immediately obtain effects on the system of changes in any one of seven parameters.

This thesis contains six sections, of which this is the first, and 2 Appendices. Section II contains a description of the system and a description of the simulation and analytic models. Section III contains a comparison of the two models under steady-state conditions. Section IV contains the analysis of the steady-state results obtained with the analytic model and effects of transportation delays and spare engine buying plans obtained with the simulation model. Section V contains the explanation of the interactive computer model. Section VI summarizes this study. Appendix A contains sample inputs and outputs of the interactive computer program. Appendix B contains the simulation and analytic model computer programs.

II. THE MODELS

A. SYSTEM TO BE MODELED

Before starting any discussion of the two models, we describe the system to be modeled. The SPRUANCE CLASS destroyers are to be powered by the General Electric LM-2500 gas turbine engines. The maintenance policy for these engines states that only a minimum amount of onboard maintenance is to be performed by ship's personnel. Instead, the engines are designed for easy removal and replacement, so that failed engines can be shipped to a central rework facility for maintenance. This sort of maintenance policy requires that spare engines be purchased to replace those that are undergoing rework. The purpose of this is to keep the fleet operational as much of the time as possible by replacing failed engines.

The typical cycle of an engine begins with an engine operating in the fleet. Based on a policy of age replacement, engines are removed from the fleet either when they have accumulated a specified number of operating hours, or when an actual failure occurs prior to the specified removal time. When an engine has been removed, it is transported to the rework facility. This shipping causes a delay in the engine's arrival at the rework facility. Once at the rework facility an engine may or may not begin rework depending on whether the rework facility is congested. However, once inducted into a rework line, each engine

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requires a known amount of time to be reworked. When rework
has been completed, the engine is placed in a ready-for-
issue status to await a requirement for use in the fleet.
There is usually no delay in transportation from the ready-
for-issue pool to a ship, since a ship can predict in advance
when an engine will reach its scheduled removal time. How-
ever, if a failure occurs early, the engine would experience
a delay being sent to the ship. A block diagram of this
system is shown in Figure 1.

B. THE SIMULATION MODEL

The computer simulation model is a General Purpose
Simulation System/360 event stored routine. This model
begins operation by generating a transaction, in this case
the first ship delivery, which sets everything into motion.
The effects of this transaction are as follows:

1. It causes the rotatable pool to be loaded in accor-
dance with the loading instructions provided in the model.
This model provides for loading the entire quantity at time
zero or at any other time during the simulation, or to load
increments up to some total quantity at various times during
the simulation.

2. It causes the simulation clock to start. The model
is run with increments of one week as the basic unit of
time, i.e., the parameters are all scaled to weeks. The
system is observed at the end of each week and the status of
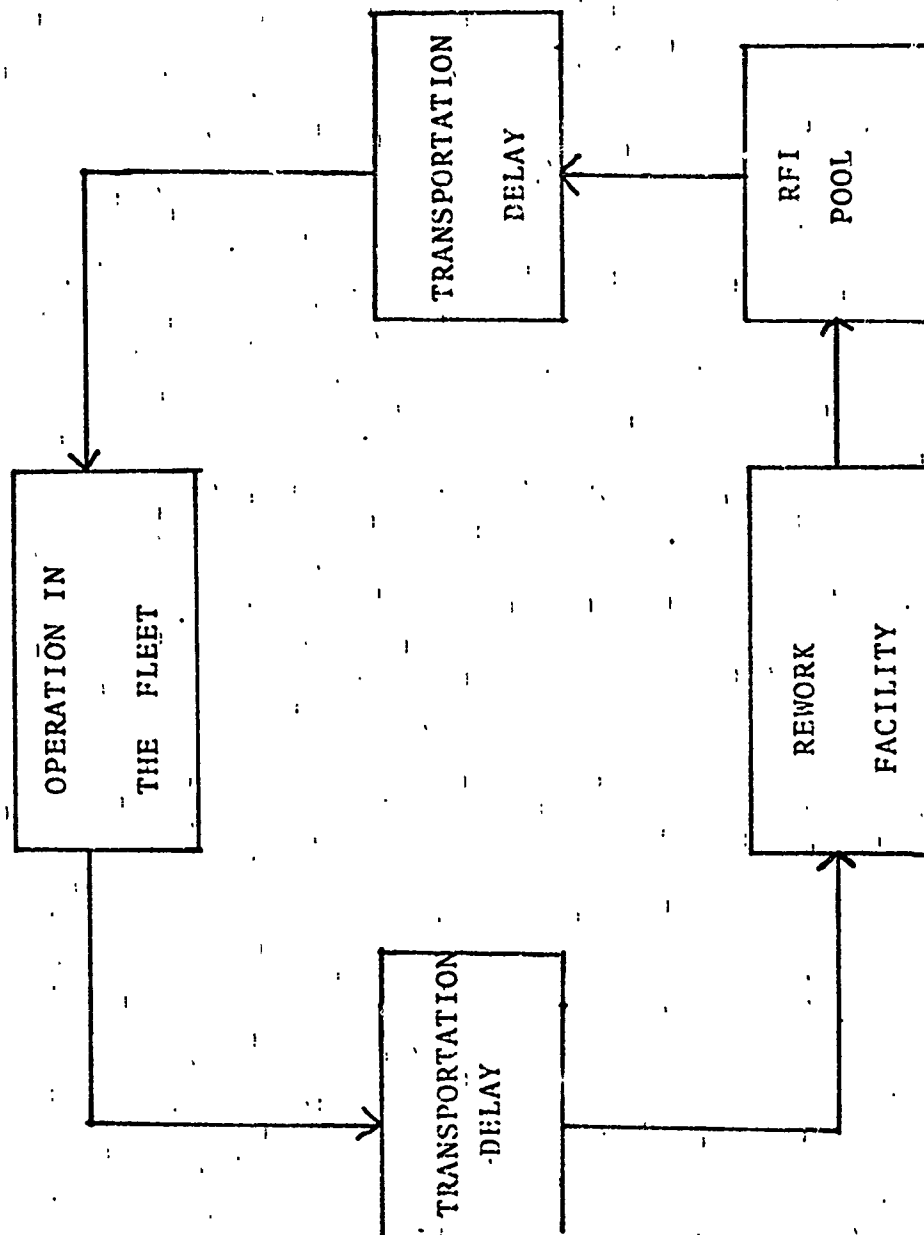the operating fleet, rotatable pool, repair lines, etc. is
recorded.

Figure 1. Block diagram of system to be modeled.

3. It causes operating units to be introduced. The model has the flexibility to provide for a build-up in the number of units operating by some prescribed delivery schedule, e.g., introduction of four engines with each DD-963 class destroyer in accordance with the ship's delivery schedule.

Various maintenance plans may be used, from the presently planned age-replacement policy, to one of removal based on some form of condition monitoring. In each case, a function determining the time to removal of each engine must be provided to the model.

A time to removal is assigned to each engine as it arrives in the operating fleet by a Monte Carlo technique, whether from new ship delivery or as a replacement engine drawn from the rotatable pool.

As the time period arrives for an engine to be removed, it leaves the fleet and a replacement is drawn from the pool, if available. Otherwise, replacement will be made with the first engine available at the pool. The removed engine proceeds to the repair facility, either directly, or through a transportation delay, if required.

Upon arriving at the repair facility, the engine is inducted on a first-come-first-served basis. If the repair lines are all busy, the engine is held in a queue until a repair line becomes available.

The engines proceed through repair in accordance with the repair function which assigns a time to repair for each engine inducted.

Upon completion of repair, the ready-for-issue engines then proceed directly to the rotatable pool where they remain until called for by the requirements of the operating fleet.

The parameters which must be specified as inputs to the simulation are:

1. The ship delivery schedule.
2. The number of engines per ship.
3. The function to generate engine removal times.
4. The rotatable pool loading plan, in time increments and quantity to be loaded each increment of time.
5. The transportation delays, if required.
6. The number of repair lines.
7. The function describing the time to repair.
8. The time for which the simulation is to run.
9. The standard GPSS statistics desired as output, or any special outputs desired.

The model typically requires about 2.5 minutes of computer time to provide statistics for ten iterations, each of 20 years duration for parameters in the ranges of interest.

C. ANALYTICAL MODEL

The LM-2500 gas turbine engine use/rework cycle can also be described in terms of a finite cyclic queue model. We make the following three assumptions:

1. There is no delay in the transportation of engines to and from the rework facility.

2. The repair time at the rework facility is exponentially distributed with rate

$$\mu_1 = 1/T_1,$$

where T_1 is the average time to rework an engine.

3. The time an engine operates in the fleet is exponentially distributed with rate

$$\mu_2 = 1/T_2,$$

where T_2 is the mean number of weeks required for an engine to accumulate a specified number of operating hours.

The consequences of all three of the above assumptions will be discussed when this model and the simulation model are compared in section III. Under these assumptions, one can determine equations for the various system performance measures.

In order to discuss the model more easily, we define the following parameters:

N = The total number of engines in the inventory. This includes both the number of engines to be installed in the fleet and the number of spare engines.

A = The number of engines to be installed in the fleet.

M = The number of repair lines in the rework facility.

Let us now define two stages for the system. An engine must be in one of these two stages. Stage 1 (The rework facility) is an M-server queue each with an exponential service time with mean rate μ_1. When all M repair lines are busy an incoming engine waits in a queue for rework. Stage 2 (The fleet) is an A-server queue each with an exponential service rate μ_2. When all ships have their full

complement of engines, a ready-for-issue (RFI) engine waits
in a pool until there is a demand from the fleet for an
engine.

The two stages form a closed system in that no engines
enter or leave the system. Since N will remain constant,
we can define

P_i = Probability there are i engines in stage 1 (hence,
N-i engines in stage 2).

For the finite cyclic queue just described, where the
number of spare engines is greater than or equal to the
number of repair lines in the rework facility, i.e.

$$N-A \leq M,$$

Koenigsberg in reference [2] determines the P_i to be:

$$P_i = (A^i/i!)(\mu_2/\mu_1)^i \, P_0, \quad 0 \leq i < M, \qquad (1a)$$

$$= (A^i/M! \, M^{i-M}) \, (\mu_2/\mu_1)^i \, P_0, \quad M \leq i \leq N-A, \qquad (1b)$$

$$= (A! A^{N-A}/(N-i)! M! M^{i-M})(\mu_2/\mu_1)^i, \quad N-A < i \leq N. \quad (1c)$$

It is also necessary that
$$\sum_{i=0}^{N} P_i = 1. \qquad (2)$$

These P_i will be used to calculate the various system
measures.

Writing the ith equation as

$$P_i = a_i \, P_0, \qquad (3)$$

then summing over i on both sides of (3) gives

$$P_0 \sum_{i=0}^{N} a_i = 1. \tag{4}$$

Therefore

$$P_0 = 1 / \sum_{i=0}^{N} a_i. \tag{5}$$

Substituting (5) into (3) we obtain

$$P_i = a_i / \sum_{i=0}^{N} a_i, \quad i = 0, 1, \ldots, N. \tag{6}$$

Direct computation of the a_i's leads to numerical problems. For example, let $N = 140$, $M = 6$, and $A = 120$. Then

$$a_{120} = \frac{120! \ (120)^{20}}{20! \ 6! \ 6^{114}}.$$

Direct computation of such a number in any machine will lead to problems since $100!$ is of the order of 10^{157}. Thus, we use the following recursive forms to calculate these coefficients:

Note that $a_0 = 1$, and let $\rho = (\mu_2 / \mu_1)$. Then

$$a_i = \frac{a_{i-1} \ A \ \rho}{i}, \qquad 1 \leq i \leq M, \tag{7a}$$

$$= \frac{a_{i-1} \ A \ \rho}{M}, \qquad M < i \leq N-A, \tag{7b}$$

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$$= \frac{a_{i-1}\, \rho\, (N+2-i)}{M} \quad , \quad N-A < i \le N. \qquad (7c)$$

In reference [2], Koenigsberg defines certain measures of system performance. The measures are interpreted in terms of the LM-2500, use/rework cycle.

$\bar{n}_1$ = Mean number of engines in the rework facility and adjoining waiting line,

$$= \sum_{i=0}^{N} i\, P_i.$$

$\bar{n}_2$ = Mean number of engines in the fleet and adjoining RFI pool,

$$= N - \bar{n}_1.$$

$\bar{w}_1$ = Mean number of engines awaiting rework,

$$= \sum_{i=M+1}^{N} (i-M)\, P_i.$$

$\bar{w}_2$ = Mean number of RFI engines,

$$= \sum_{i=0}^{N-A} (N-A-i)\, P_i.$$

d_1 = Percent time all repair lines are busy,

$$= \left(\sum_{i=M}^{N} P_i \right) \times 100$$

H_1 = Mean number of engines being repaired,

$$= \bar{n}_1 - \bar{w}_1.$$

H_2 = Mean number of engines operating in the fleet,

$\quad = \bar{n}_2 - \bar{w}_2$.

U_m = Mean percent rework capacity used,

$\quad = (H_1/M) \times 100$.

U_n = Mean percent of total engines in operation in the fleet,

$\quad = (H_2/N) \times 100$.

Three additional system measures not given by Koenigsberg in reference [2] are also included in the output. The first is cycle time (C). This is the average time required for an engine to complete a full cycle of the system. To derive this measure, we first note that the rate into a stage is equal to the rate out of the same stage. Then in steady state the rate out of the fleet stage is $\mu_2 H_2$. This is the rate everywhere in the system, so the cycle time (C) is given by

$$C = N/\mu_2 H_2 \ .$$

To calculate the probability the fleet is short i or more engines ($P_s(i)$), we use the following:

$$P_s(i) = 1 - \sum_{i=0}^{N-A+1} P_i \ .$$

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To calculate the average number of engines short in the
fleet ($\bar{s}$), we use

$$\bar{s} = A - H_2 .$$

All of the above measures of system performance are printed
in the output except $\bar{n}_1$ and $\bar{n}_2$ which are only used to cal-
culate other measures.

 ` There are seven parameters of the LM-2500 use/rework
cycle which serve as the inputs to the model. They are:

1. Number of ships (S),
2. Number of engines per ship (E),
3. Number of spare engines (P),
4. Number of repair lines (M),
5. Average rework time per engine in weeks (T_1),
6. Time between overhauls (TBO),
7. Engine operating hours per year (TOR).

The above seven parameters are converted internally in
the program to the actual parameters used by the model in
the following way:

$$A = S \times E,$$
$$N = A + P,$$
$$\mu_1 = 1/T_1,$$
$$T_2 = (TBO/TOR) \times 52 \times 0.9,$$
$$\mu_2 = 1/T_2$$
$$M \text{ is unchanged.}$$

All of the above are self explanatory except T_2. This
equation for T_2 is explained fully in the section on compar-
ison of the models. Briefly, it calculates a mean time to
replacement consistant with the age replacement policy for
engine removals.

III. COMPARISON OF MODELS

The simulation model was developed because "... analysis
of the DD-963 inventory problem disclosed that system com-
plexities rendered analytical modeling infeasible." (See
[1] , page 17) That is true if all of the transient prob-
lems are to be included. However, inclusion of the rela-
tively short transient period in a long-term program could
lead to decisions which are harmful in the long-term. For
that reason, steady-state results from the simulation and
the analytical model were compared to determine any differ-
ences in results from the two models. Since the analytical
model has certain restrictions, e.g., no capability to
handle transportation delays, the simulation model was
modified to eliminate transportation delays and to elimin-
ate the transient effects by introducing the 30 ships and
loading the pool at time zero.

The two models were run with the same parameters over
various ranges. The results of the two models were extremely
close, with the analytical model consistently more conser-
vative than the simulation model. Most important, as shown
by Figures 2, 3, and 4, the response to changes in particu-
lar parameters followed the same pattern in the two models.
As an example, the average number of engines awaiting repair
plotted against rotatable pool size, with the 4,000 hour TBO,
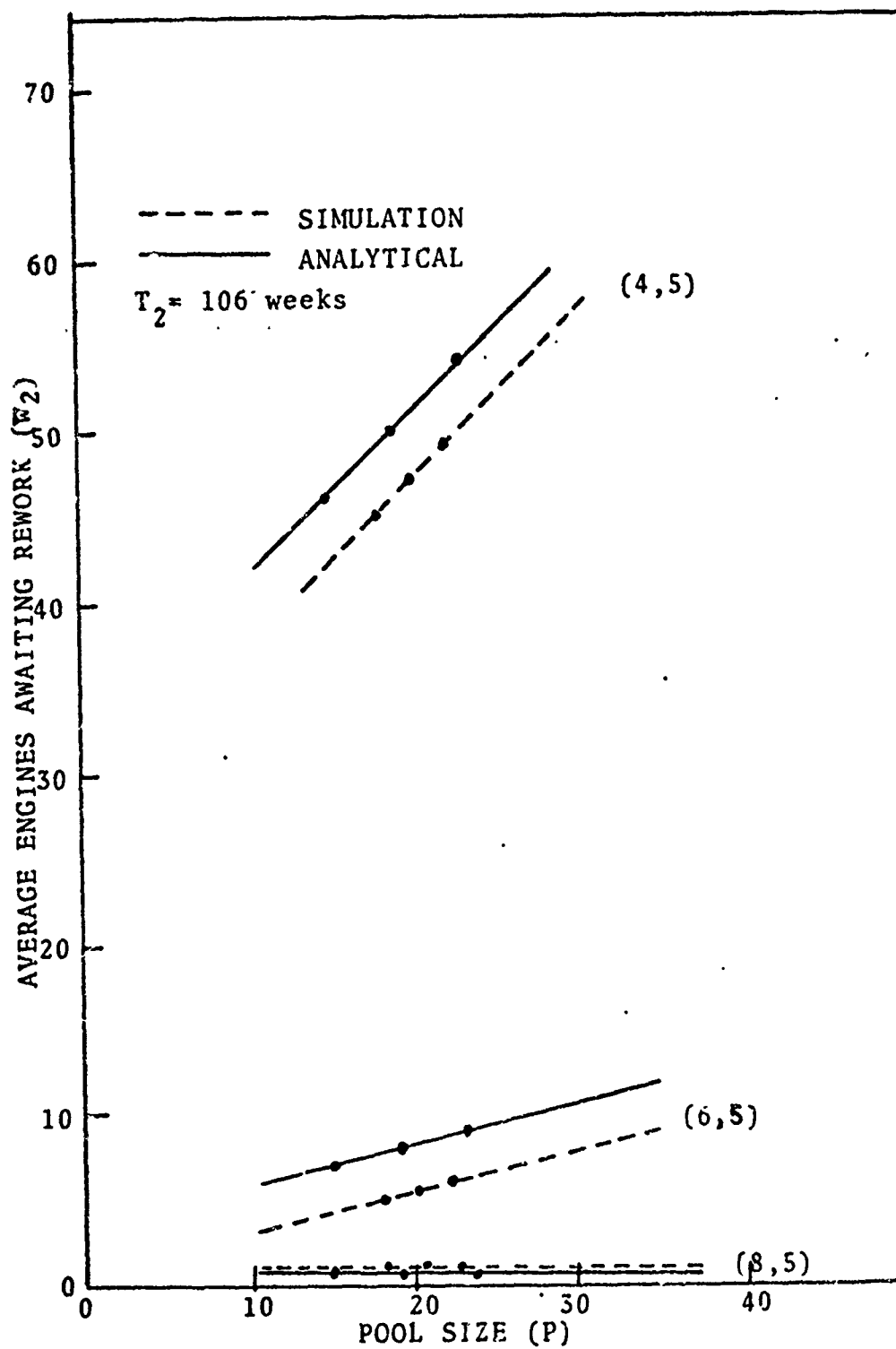2,000 annual hours per engine, repair time of 5 weeks, and

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Figure 2. $\widetilde{W}_2$ vs. P.

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Figure 3. U_m vs. M.

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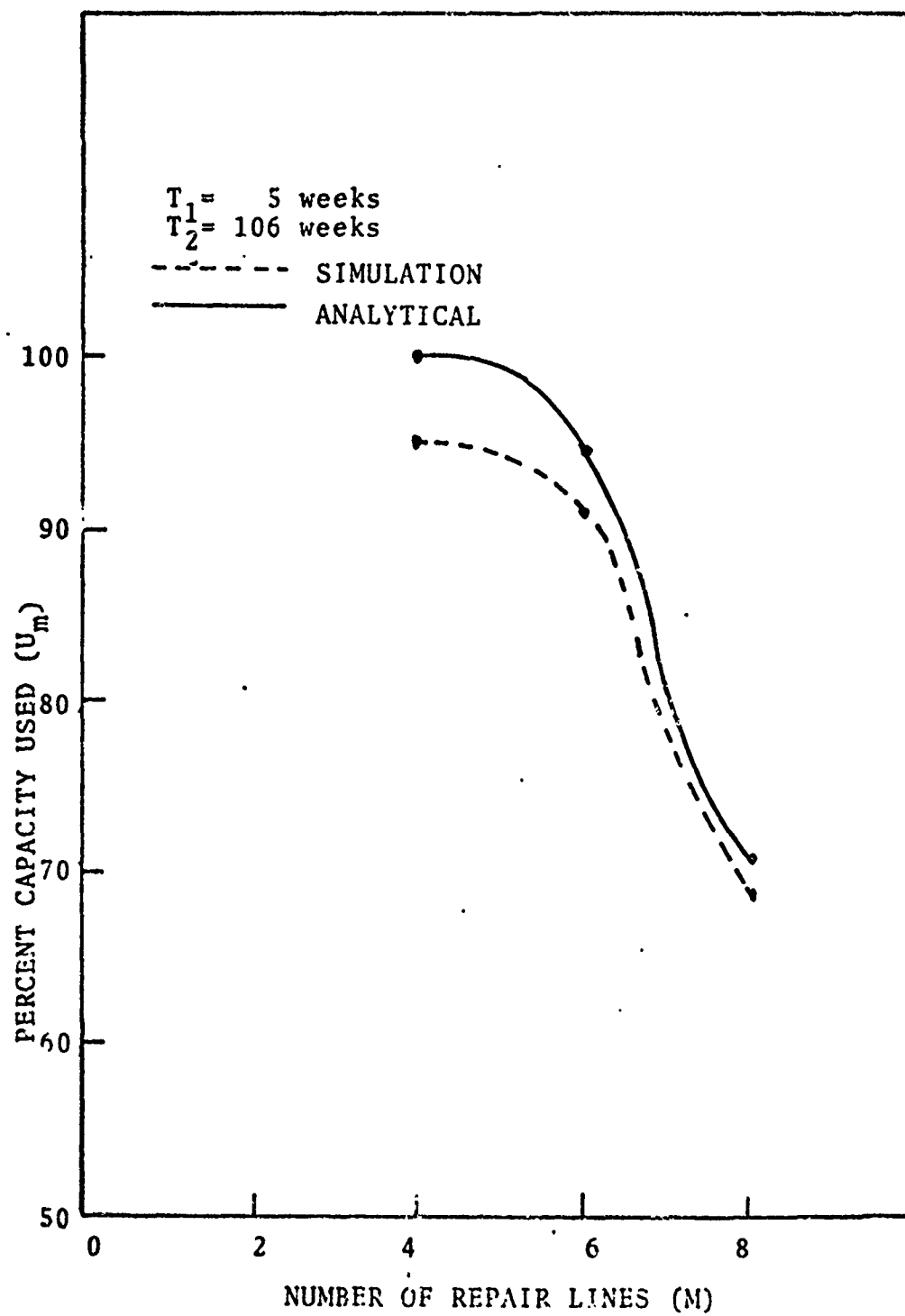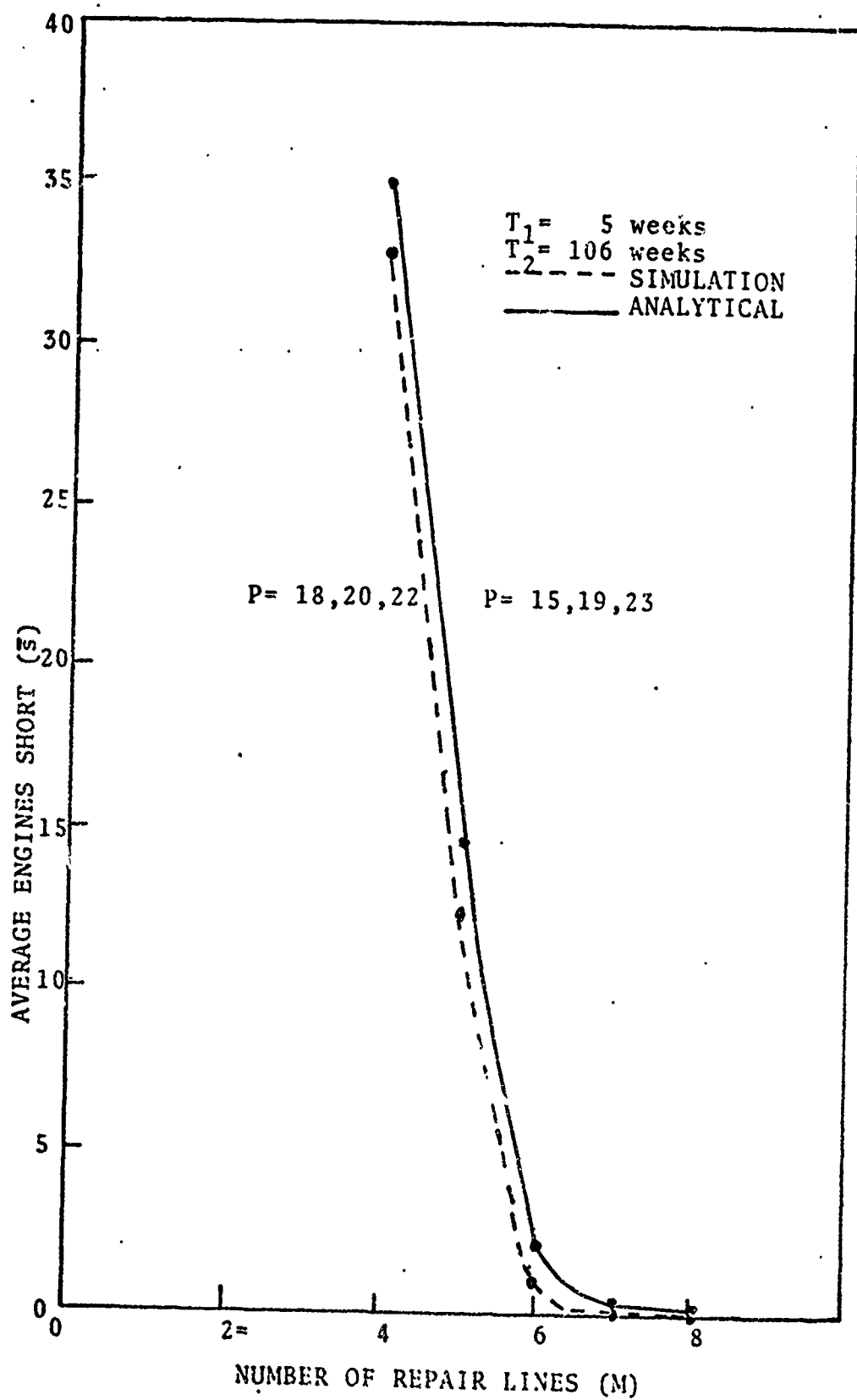
Figure 4. $\bar{s}$ vs. M

4, 6, and 8 repair lines, is displayed in Figure 2. While the number waiting is slightly less with the simulation model than with the analytical model, both models show the same behavior with a change in pool size. For a repair facility with only 4 repair lines and a pool size of 15, the waiting line is long, 42 for the simulation model and 46 for the analytical model. However, more important is that each additional engine added to the pool increases the size of the waiting line by one engine for both models. Similar results are evident with the other comparisons in Figures 3 and 4.

Although from the foregoing model comparison we conclude that both give the same steady-state results, it should be pointed out that the time in the fleet and repair time distributions used in the two models were very different. This shows that the analytical mode is quite robust and deviation from the exponential distributions do not lead to serious errors.

In the simulation model, the time an engine stays in the fleet has an empirically determined distribution function, constructed by Cushing, Gautier, and Long [1] using actual records of DD type operations. The analytical model has an exponential distribution function with a mean time in the fleet determined by the TBO and TOR. The repair time for the simulation is deterministic, whereas the analytical model uses an exponential distribution function

with a mean repair time equal to the deterministic value
of the simulation.

In our comparison of the distributions of the time an
engine stays in the fleet, the 4,000 hour TBO and 2,000 TOR
operating profile are used. These result in a mean time
in the fleet of 106 weeks which is used in the exponential
distribution.

As previously explained in the simulation model, a
time, in weeks, for an engine to reach 4,000 hours is a
random variable which we will define to be X. The distri-
bution of X is discrete with the following mass function:

x	$P(X=x)$
66 weeks	.009
72 "	.019
78 "	.019
84 "	.027
90 "	.046
96 "	.055
102 "	.076
108 "	.093
114 "	.120
120 "	.120
126 "	.120
132 "	.102
138 "	.074
144 "	.037
150 "	.029
156 "	.019
162 "	.019
168 "	.009
174 "	.009
elsewhere	.000

Once X is determined for an engine, there is a 0.8
probability that the engine will be removed at that time and
a 0.2 probability that it will fail before the time X. The

distribution of the time for the early failure is assumed
to be uniform between zero and X weeks.

The distribution of the time in the fleet is a random
variable Y, a function of the random variable X, the U(0,X)
random variable, and the probability of reaching the de-
sired TBO. The conditional distribution of Y given X is:

$$P(Y \leq y \mid X = x) = \begin{cases} \dfrac{.2y}{x} & \text{for } y < x, \\ 1 & \text{for } y \geq x. \end{cases}$$

Figure 5 is a sample of the conditional distribution of Y.
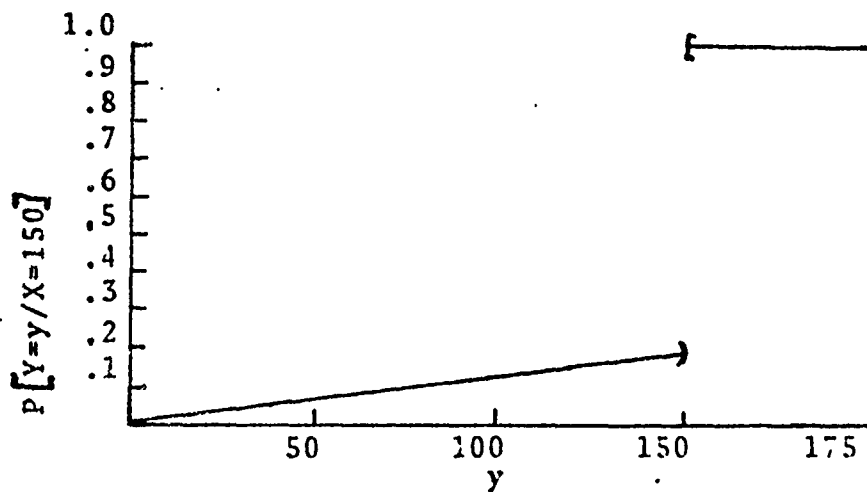
Figure 5. Sample Conditional Distribution of Y given X

The unconditional distribution of Y is

$$P(Y \leq y) = \sum_{x=0}^{y} p(x) + \sum_{x=y+1}^{174} \frac{.2y}{x} p(x) .$$

A plot of this distribution function is displayed in Figure 6 along with the exponential distribution function with the same mean.

While the two functions are clearly quite different, the probability of a removal prior to 128 weeks of operation is approximately 0.74 for both distributions. There is a probability of approximately .16 that an engine stays in the fleet in excess of 174 weeks using the exponential distribution which is zero for the empirical distribution. This provision for times greater than 174 weeks prior to removal for some engines has a "real world" appeal.

This comparison was done with the 4,000 hour TBO and the 2,000 annual hours per engine TOR. The mean time in the fleet derived from the empirical distribution function for this combination is 106 weeks. This is derived by finding $E[X]$ and then finding $E[Y]$ as follows:

$$E[Y] = E[E[Y|X]] = E[\frac{.2X}{2} + .8X] = .9 E[X] .$$

Cushing, Gautier, and Long [1] developed empirical distribution functions for various TBO and TOR combinations. Rather than calculate the mean of each of these functions
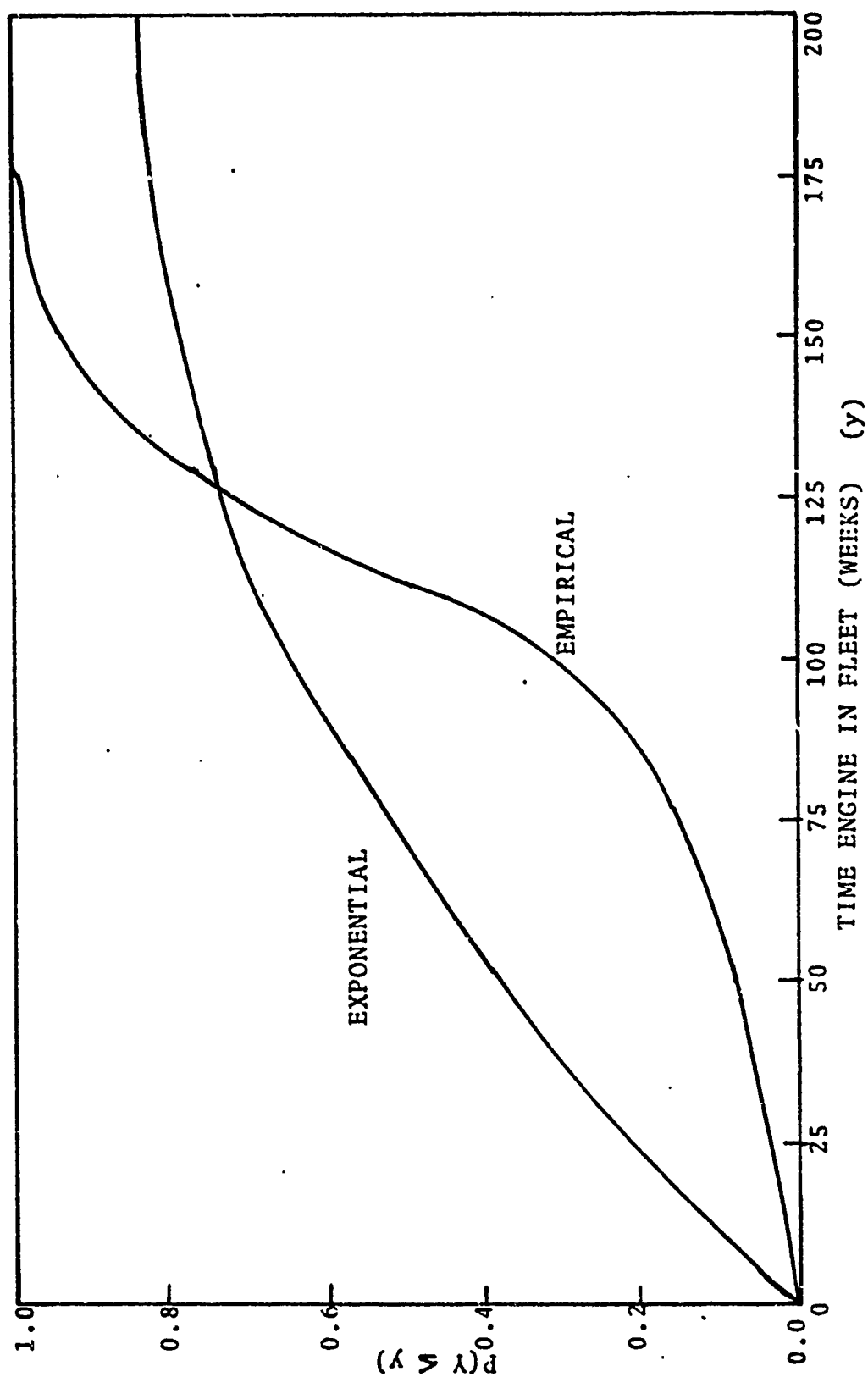
Figure 6. $P(Y \leq y)$ vs. y.

for use in the analytical model, we have defined the
following:

$$E[X] \text{ (in weeks)} = 52(TBO/TOR) \quad \text{and}$$

$$E[Y] \text{ (in weeks)} = .9E[X] , \quad \text{for all TBO and}$$
$$\text{TOR combinations.}$$

If the interest is in the number of engines that have
to be removed at exactly 30 weeks of operation in the
fleet, or some other such specific time, the two models
would not necessarily agree. But if the primary interest
is in analyzing overall results, e.g., the average number
of engines short in the fleet, then the two models give
virtually the same results.

Given the current state of the system , no one knows
which distribution will best describe the actual operations.
But for analyzing the long term behavior of the whole
system, either model could be used. The choice of which
model to use should be determined by the advantages one
might have over the other.

The analytical model is limited in that it provides only
steady-state results. For this reason, the simulation is
used to analyze the transient time problems of incremental
ship delivery, incremental pool purchases, and the addi-
tional problem of transportation delays. The analytical
model provides a rapid efficient method of measuring the
effects of changing various policy variables. The results
obtained on the computer, using the analytical model,

require about 2 seconds computer time for each set of parameters investigated, whereas the simulation requires about 2.5 minutes for the same analysis.

IV. INTERACTIVE COMPUTER PROGRAM

To provide the policy planner with a real-time system for determining the effects of various parameter changes on the LM-2500 use/repair cycle, an interactive computer program has been developed which uses the analytical model.

To operate the interactive computer system, the policy planner would require the use of a remote terminal which can be connected to the computer in which the program is stored. He would then go through a standard procedure to begin the execution of the program. This procedure is a function of the computer center so it will not be explained here.

Once execution begins, the program will print instructions for entering the use/repair cycle parameters. Seven parameters are to be entered. They are:

1. Number of ships
2. Number of engines per ship
3. Number of spare engines
4. Number of repair lines in the rework facility
5. Average rework time per engine in weeks
6. Time between overhauls in hours
7. Engine operating hours per year.

When all of these parameters have been entered, the program will type out the parameters and their value so that these can be checked for possible errors. If they are in fact correct, the user types a 1 (one), and the program will

calculate the use/repair cycle system performance measures. If they are not correct the user can type a 0 (zero), and the program will return to it's start so the correct parameters can be entered. In Appendix A, on page 50, an actual example of this input procedure is included.

On page 52, a sample of the output is also listed. This whole process of input and output requires about five minutes. The decision maker can, if he chooses, restart the program with a new set of parameters. Actual computer time per set of parameters is less than two seconds.

V. ANALYSIS

A. STEADY STATE RESULTS

Of the many measures of system performance, the following measures were chosen as providing the most information to the policy planner:

1. Average number of engines short in the fleet ($\bar{s}$),
2. Average number of RFI engines ($\bar{w}_2$),
3. Average percent of rework capacity used (U_m),
4. Average number of engines awaiting rework ($\bar{w}_1$).

When looking at these measures for various combinations of system parameters, it must be kept in mind that they are steady state results. That is, this is how the system will look after it has been operating over a long period of time. The effects of the start-up of the system have little or no effect on the value of the steady state system performance measures.

In figures 7 through 10, the four measures above are plotted versus the ratio of TBO to TOR. All four graphs are based on 19 spare engines. The effects of a change in the number of spare engines are investigated below. Table 1 converts a given TBO and TOR into the ratio shown on the graphs. In each figure, a set of nine curves is plotted. Each curve corresponds to a given number of repair lines (M) and an average repair time (T_1). Each line is labeled (M, T_1).

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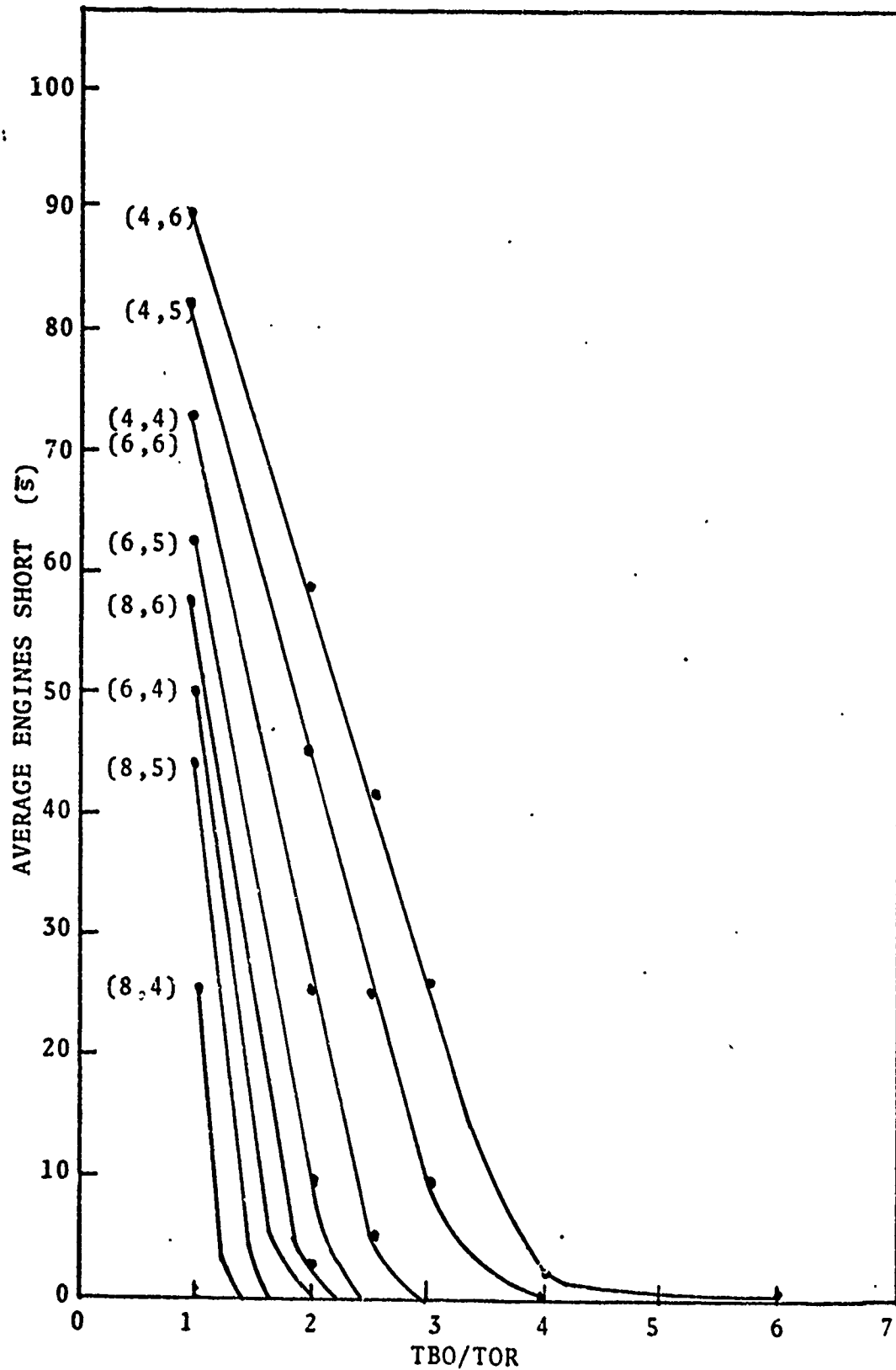
Figure 7. $\bar{s}$ vs. TBO/TOR.
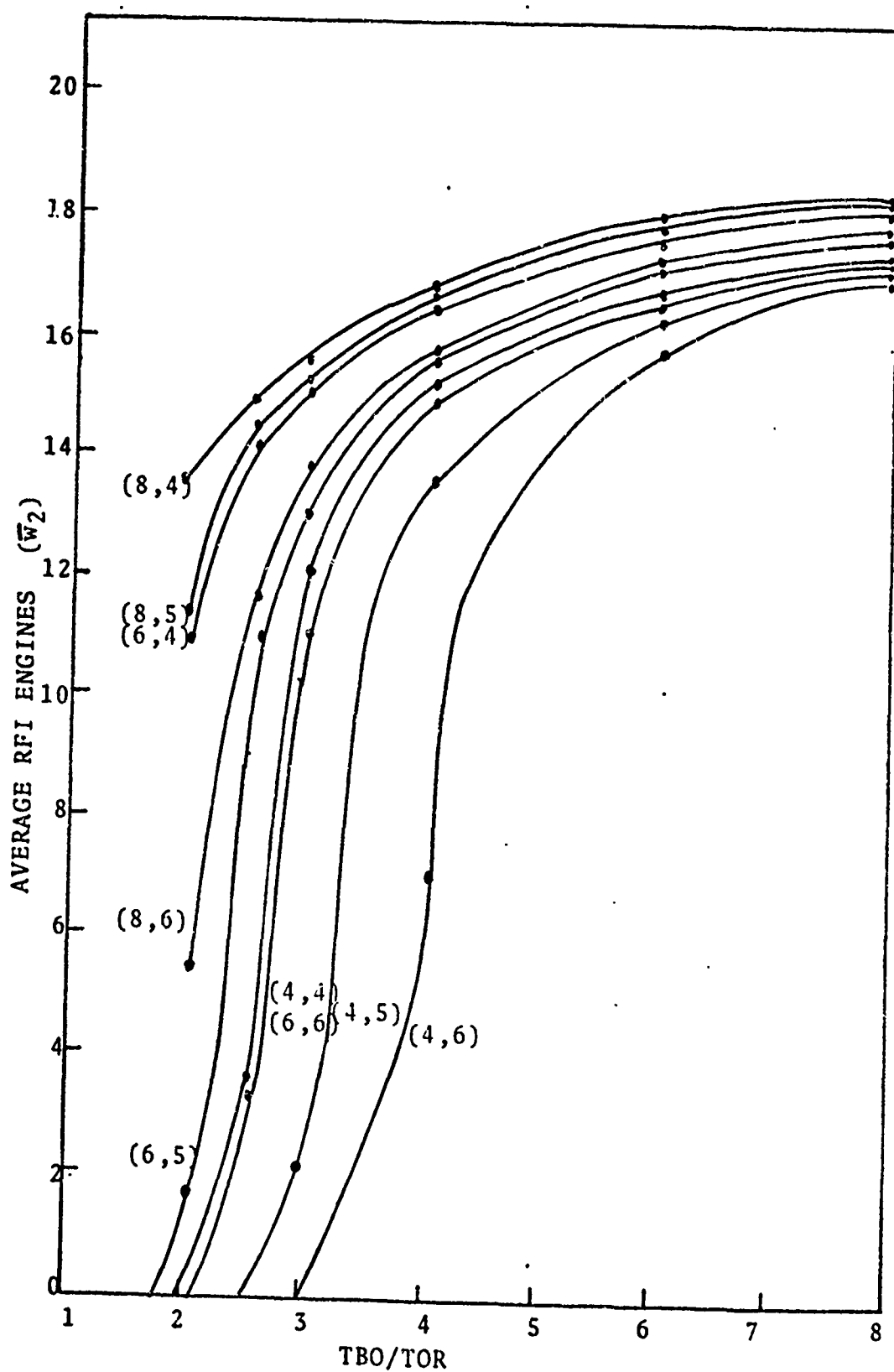
Figure 8. $\bar{w}_2$ vs. TBO/TOR.
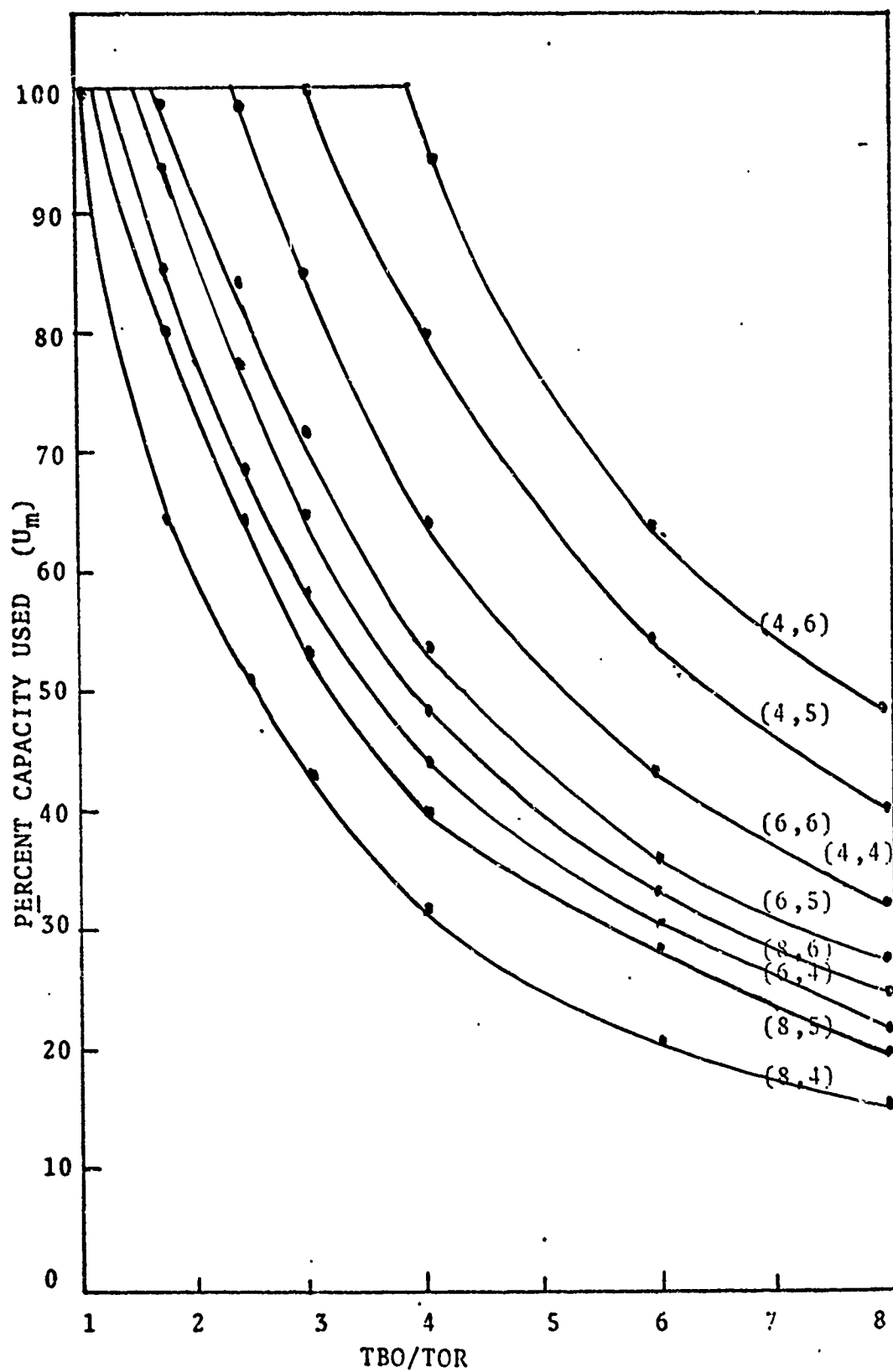
Figure 9. U_m vs. TBO/TOR.
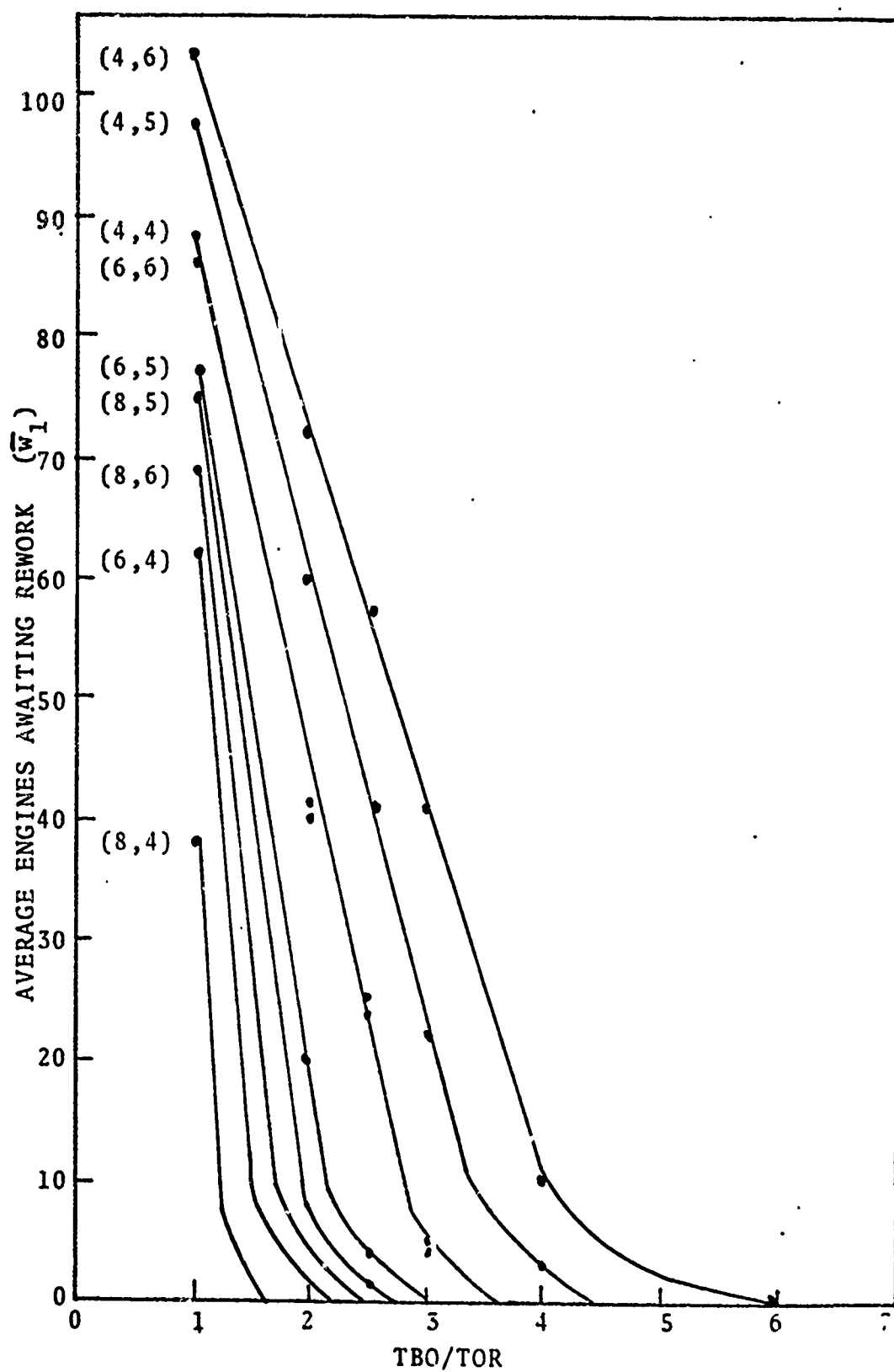
Figure 10. $\bar{w}_1$ vs. TBO/TOR.

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TABLE 1

Converts a given TBO and TOR to the ratio used in figures 7 through 10

TBO	TOR		
	1650	2000	2500
4000	2.4	2.0	1.6
5000	3.0	2.5	2.0
6000	3.6	3.0	2.4
7000	4.2	3.5	2.8
8000	4.8	4.0	3.2
9000	5.5	4.5	3.6
10000	6.1	5.0	4.0
11000	6.7	5.5	4.4
12000	7.3	6.0	4.8

Figure 7 shows the relation between average number of engines short in the fleet ($\bar{s}$) and TBO/TOR. For each of the nine curves there is a dramatic decrease in $\bar{s}$ as TBO/TOR increases to about 4, usually an increase in TBO/TOR is brought about by an increase in engine reliability. Also it can be seen that there is a strong effect due to the combination of M and T_1. That is, when there is adequate repair capacity in terms of size and speed, then the number of engines short in the fleet is reduced rapidly.

The plots of the other three measures in figures 8, 9, and 10 show the same dramatic changes as TBO/TOR is increased to about 4. The combination of M and T_1 also produce the same sharp effects as the rework facility is made more capable of reworking engines.

For example, let us look at a system where

$$M = 6,$$
$$T_1 = 5,$$
$$TBO = 4000,$$
$$TOR = 2000.$$

We will then change TBO to 6000 and look at the results of this change in TBO/TOR from 2 to 3. Now enter each figure with these two ratios. In figure 7, entering at TBO/TOR = 2 we find the value of $\bar{s}$ to be 10 on the curve labeled (6,5). When entering the graph at TBO/TOR = 3, we find that the (6,5) curve has gone to 0 for a ratio less than 3. So the change in TBO has resulted in a reduction of the number of engines short in the fleet by 10. Entering

figure 8 in the same manner, shows that the number of RFI engines is increased from 2 to about 13. From figure 9, we see that the average facility capacity used decreased from 99% to 73%. From figure 10, we see that the average number of engines awaiting rework decreased from 20 to less than 1. It is therefore quite evident that any program to increase the reliability of the engines will be of great benefit to the operating fleet and will cut down on the required rework capacity.

The above graphs were produced using 19 spare engines, with a fleet of 120 engines. A natural question is what effect will a change in the number of spare engines have on the four system measures? For this reason, the four measures are plotted versus the number of spare engines in figures 11 through 14. Each figure uses a value of $T_2 = 106$ weeks, $M = 6$, and $T_1 = 5$ weeks. In some figures, other values of M and T_1 are used and will be explained as they are needed.

Figure 11 shows the average percent of facility capacity used (U_m) versus spare engines. This measure is insensitive to changes in the number of spare engines. So when comparing U_m, the number of spare engines need not be considered.

In figure 12, the average number of engines short in the fleet is plotted. This measure does show some effects due to the number of spare engines. However, the effect is larger between 8 and 15 spare engines than between 15
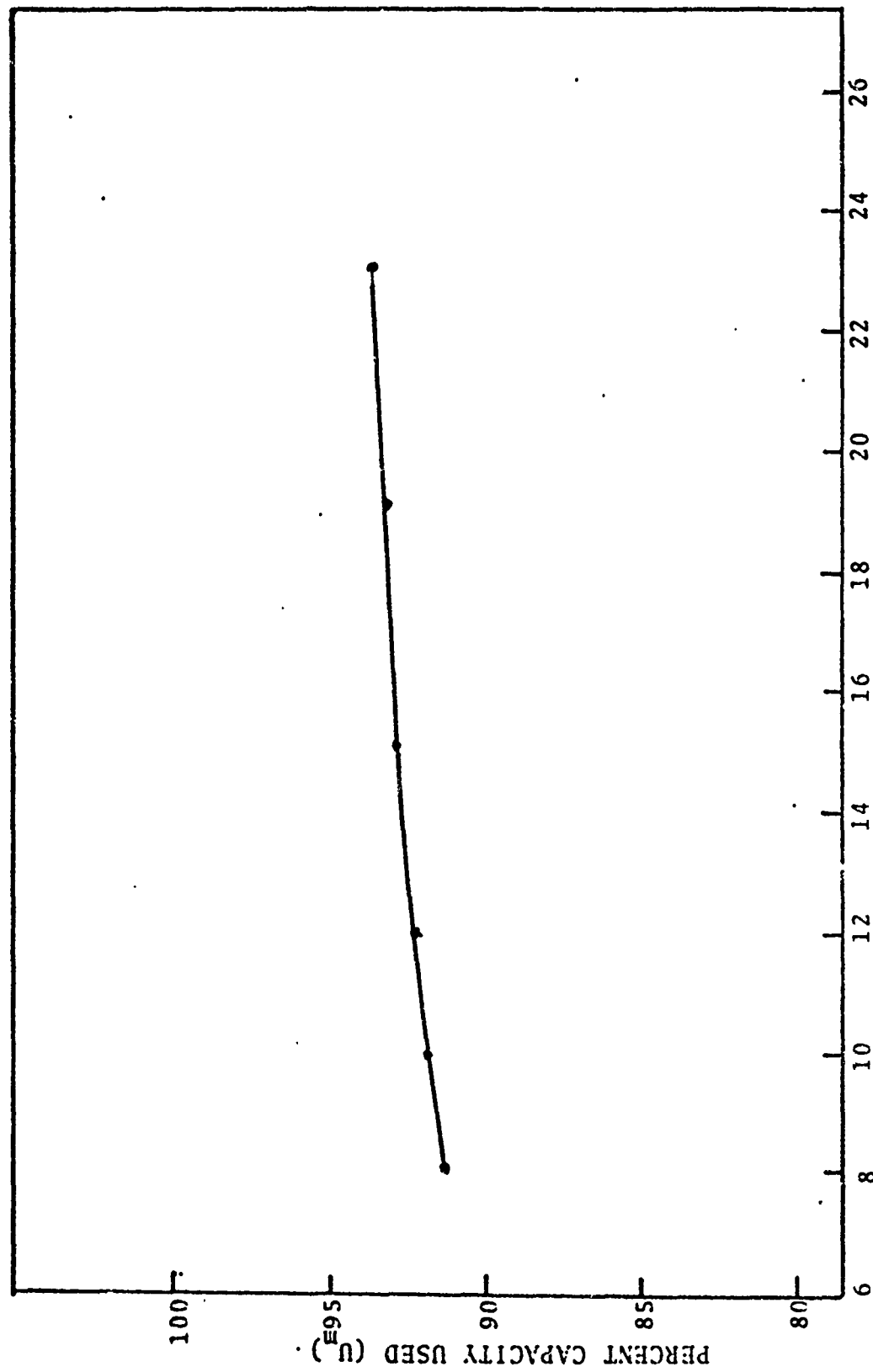
Figure 11. U_m vs. P.

Figure 12. $\bar{s}$ vs. P.

AVERAGE ENGINES SHORT ($\bar{s}$)

SPARE ENGINES (P)

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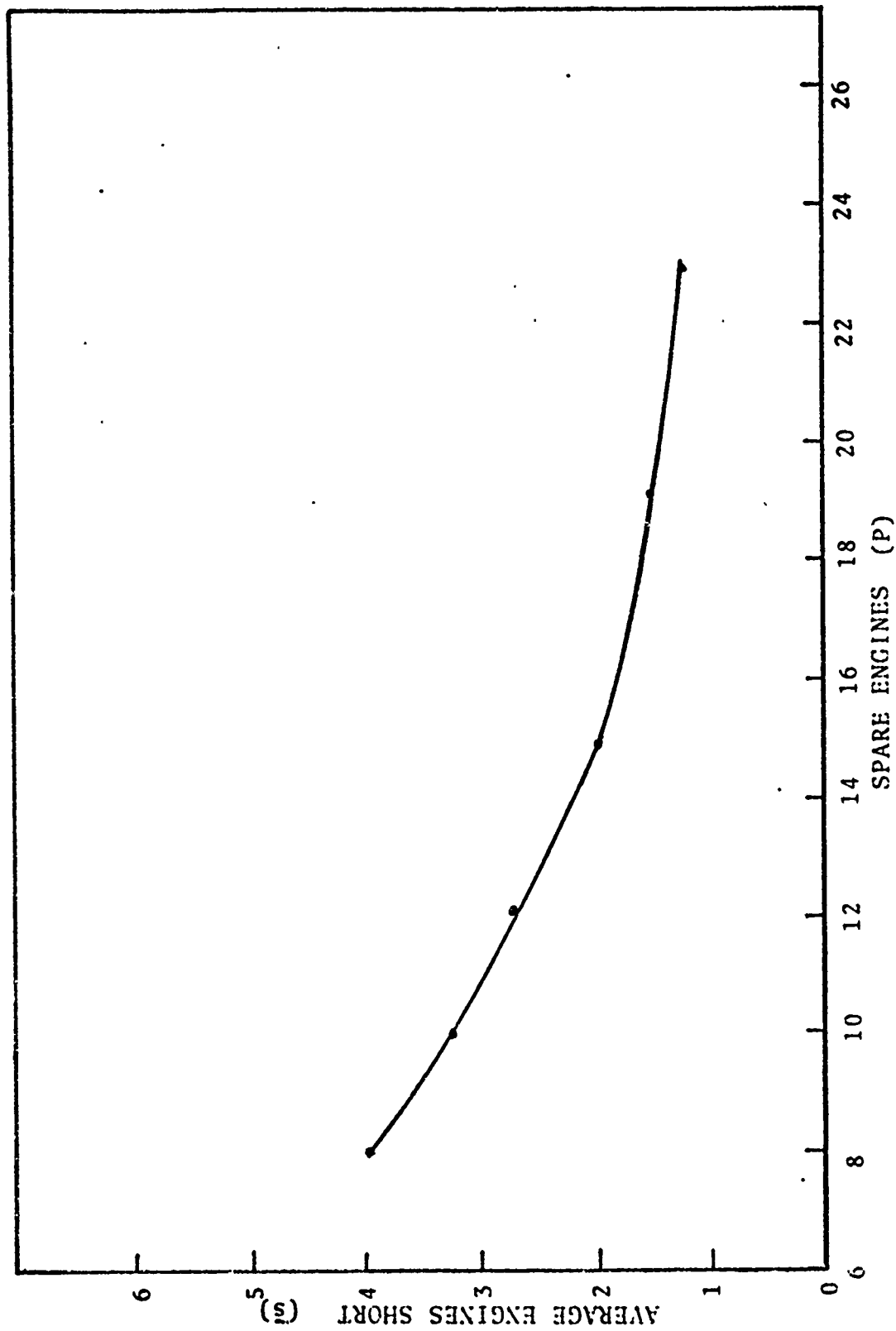
and 23 spare engines. When changing the number of spares
from 8 to 15, the number short is reduced by only 2. In
the range from 15 to 23, this reduction is only one engine.
Therefore, an increase in the number of spare engines has
very little effect in reducing shortages in the fleet.
Figure 7 shows that there is a better return received by
developing the right rework facility than buying spare
engines.

Figure 13 shows a different sort of result for the
average number of RFI engines. Whereas the average number
of engines short did not change much, this measure does.
In this case, three curves are plotted, the standard (6,5)
case, the best case (8,4), and the worst case (4,6). The
number of RFI engines is low and unchanging for the (4,6)
case. When the rework facility capacity is increased
(increase M, decrease T_1), the number of RFI engines begins
to increase with the number of spare engines. However it
is the parameters of the rework facility that are causing
the effects, not the number of spare engines. If the re-
work facility is large enough and the rework time short
enough then the spare engines end up in the RFI pool.

Figure 14 shows that the waiting line at the facility
does increase with an increase in the number of spare
engines. This is perhaps the best evidence that if there
is not enough rework capacity, an increase in the number
of spare engines will not help the operating fleet. The
engines merely add to the length of the rework waiting

Figure 13. $\bar{w}_2$ vs. P.

43
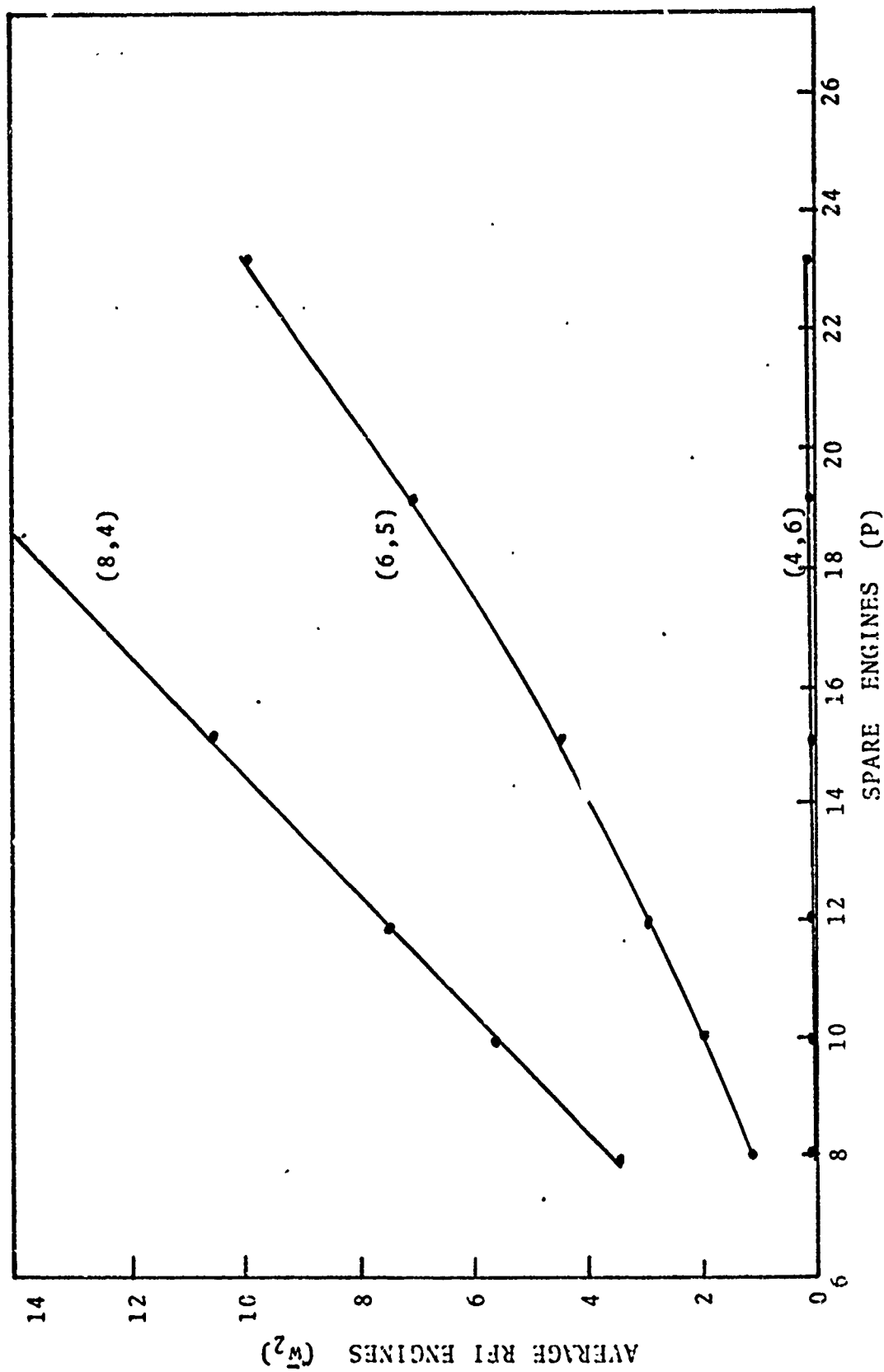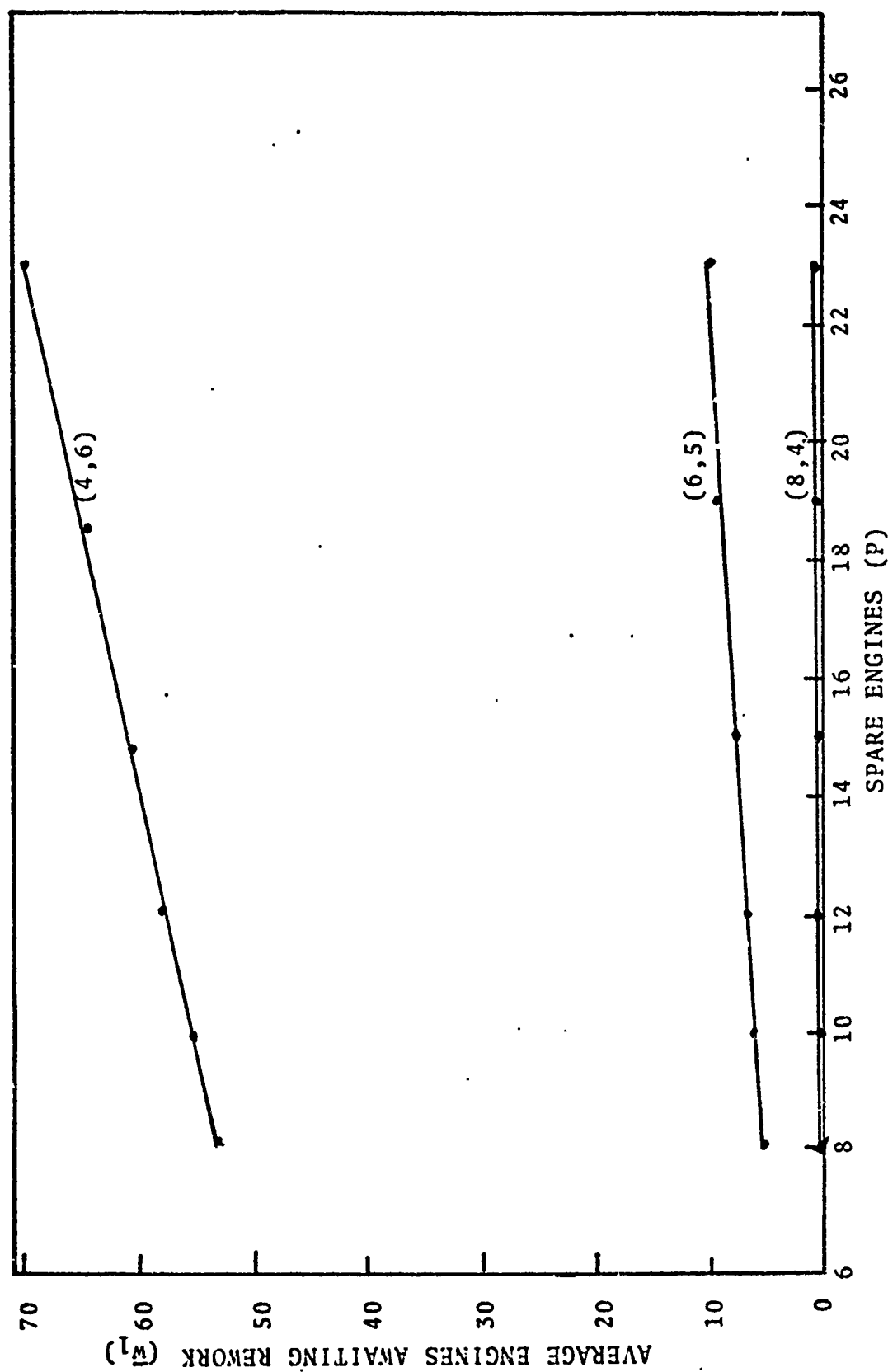
Figure 14. $\bar{w}_1$ vs. P.

line. The slope of the curves approaches 1 as the rework
facility parameters approach their worst case. So in the
long run, to buy spares to keep the fleet operating will
not accomplish its purpose unless it is accompanied by a
corresponding increase in rework facility capacities.

B. TRANSPORTATION DELAYS

The analytical model could not include the delays which
are incurred between removal from the ship and arrival at
the repair facility, and the similar delay incurred between
the RFI pool and the fleet when an unscheduled removal is
experienced. For these reasons, the simulation model was
used to determine the effects of transportation delays.

The simulation model was run with the 120 engine oper-
ation, a pool size of 19, repair time of 5 weeks, 6 repair
lines, and transportation delays in both of the above cases
of 0,2,3,4, and 8 weeks. The average number of engines
short in the fleet was observed in each case with the
following results:

Transportation Delay	Ave. # engines short in fleet
0	0.3
2	1.7
3	2.8
4	3.8
8	8.3

This indicates that each week of transportation delay
costs the operating fleet an average of one engine. This
might be interpreted to mean that an increase in pool size
of one for each week of transportation delay would counteract

the effect of 1 week transportation delay. To test this,
for the transportation delay of eight weeks, the pool size
was increased from 19 to 27 and the simulation repeated.
The average number of engines short decreased to 4.3 from
8.3. Thus, two additional engines in the pool were required
to reduce the number short in the fleet by 1.

C. TRANSIENT RESULTS

Two different spare-engine buy plans were tested with
the simulation model. Each plan was for a total pool size
of 19. The plans were tested with the 4,000 hour TBO,
2,000 annual operating hours per engine TOR, repair time of
5 weeks, 6 repair lines, transportation delay of two weeks,
and the DD-963 planned delivery schedule. The buy plans
tested were:

| Delivery Dates | | Number of engines | |
Test 1	Test 2	Option 1	Option 2
1 Jul 75	1 Jan 76	5	2
" 76	" 77	5	3
" 77	" 78	3	3
" 78	" 79	3	5
" 79	" 80	3	6

Using the percentage of time there are no engines in
the pool over a twenty year period as a measure to compare
the effects of the two buying plans, the following results
were obtained:

Option 1,	Test 1	92.7%
Option 2,	Test 1	91.9%
Option 1,	Test 2	92.8%
Option 2,	Test 2	92.0%

This indicates that the system is relatively insensitive to the differences in these two buy plans over reasonably long time periods. The particular plan selected should probably be determined by economic considerations in the short term, say the first 5 years. It was felt that the simulation model did not provide reliable analysis of the short term effects of the two buy plans.

VI. SUMMARY

Using as measures a) the average number of engines short in the fleet, b) the average number of engines in the RFI pool, c) the percentage of repair capacity used, and d) the average number of engines awaiting rework, the significant findings of this study can be summarized as follows:

1. In the long run, the four measures are extremely sensitive to the ratio of time between overhaul to annual engine operating hours. The system is improved by a higher ratio.

2. In the long run, the four measures are extremely sensitive to the repair facility capacity as measured by the number of repair lines and average engine repair time.

3. In the long run, the percentage of repair capacity used and the average number of engines short in the fleet are relatively insensitive to the number of spare engines purchased. However, the average number of engines in the RFI pool and the average number of engines awaiting rework are extremely sensitive to the number of spare engines purchased. The additional spares end up in an inactive status over the long run. If there is excess repair capacity, they end up in the RFI pool. If there is insufficient repair capacity, they end up in the repair facility waiting line. For cases in between they are split between the RFI pool and the repair facility waiting line.

4. The interactive computer system developed for use with the analytical model provides a useful method for the policy planner to immediately see the effects of changes in system parameters.

APPENDIX A

INTERACTIVE COMPUTER PROGRAM INPUT/OUTPUT FORMAT

EXECUTION BEGINS...

DATE   08/30/72

DETERMINATION OF OPERATIONAL CHARACTERISTICS OF LM 2500
USE/REWORK CYCLE.

AFTER EACH PARAMETER EXAMPLE, ENTER YOUR PARAMETER CHOICE
IN THE FORMAT SHOWN.

1.   NUMBER OF SHIPS
EXAMPLE 30   (YOU ENTER NUMBER XX   AND HIT RETURN)
30

2.   NUMBER OF ENGINES PER SHIP
EXAMPLE 4 (X)
4

3.   NUMBER OF SPARE ENGINES
EXAMPLE 20   (XX)
19

4.   NUMBER OF REPAIR LINES
EXAMPLE 06   (XX)
06

5.   AVERAGE REWORK TIME PER ENGINE (WEEKS)
EXAMPLE 5   (X)
5

6.   TBO (TIME BETWEEN OVERHAULS, HOURS)
EXAMPLE 4000   (XXXX)
4000

7.   ENGINE OPERATING HOURS PER YEAR
EXAMPLE 2000   (XXXX)
2000

CHECK YOUR PARAMETER CHOICES

NUMBER OF SHIPS   30

NUMBER OF ENGINES/SHIP   4

NUMBER OF SPARES   19

NUMBER OF REPAIR LINES   6

AVERAGE REWORK TIME   5

TBO   4000

ENGINE OPERATING HOURS   2000

ARE THESE CORRECT?   IF YES TYPE 1
IF NO TYPE 0, PROGRAM WILL RESTART
1

LM-2500 USE/REWORK SYSTEM PERFORMANCE MEASURES

REWORK FACILITY STATISTICS

AVERAGE NUMBER OF ENGINES AWAITING REWORK	20.0
AVERAGE NUMBER OF ENGINES BEING REWORKED	5.9
AVERAGE % CAPACITY USED	99.1
% TIME ALL REPAIR LINES BUSY	97.3

FLEET/POOL STATISTICS

AVERAGE NUMBER OF ENGINES IN FLEET	111.3
AVERAGE NUMBER OF ENGINES SHORT IN FLEET	8.7
AVERAGE NUMBER OF ENGINES READY FOR ISSUE	1.8
AVERAGE % ENGINES OPERATIONAL	80.0
AVERAGE CYCLE TIME (WEEKS)	116.9

% TIME FLEET IS SHORT	1 OR MORE ENGINES	71.9
	6	57.6
	11	40.0
	16	22.6

DO YOU DESIRE TO RUN ANOTHER SET OF PARAMETERS?
IF YES, TYPE 1; IF NO, TYPE 0
0

```
*****************************************
*                                       *
*     GPSS SIMULATION MODEL COMPUTER PROGRAM     *
*                                       *
*****************************************

         SIMULATE
         RMULT      11,77
         INITIAL    XH$INT,K1
         INITIAL    XH$TRANS,K2      AVERAGE TRANSPORTATION DELAY
         INITIAL    XH$REWORK,K5     AVERAGE REWORK TIME
         INITIAL    XH$RAND,K200     PERCENT EARLY FAILURES
*                                    LOADING SCHEDULE FOR ROTATABLE POOL
         INITIAL    XH$LOAD1,0/XH$LOAD2,5/XH$LOAD3,5/XH$LOAD4,3
         INITIAL    XH$LOAD5,3/XH$LOAD6,3
         INITIAL    XH$TIME2,30/XH$TIME3,52/XH$TIME4,52/XH$TIME5,52
         INITIAL    XH$TIME6,52
FAC      STORAGE    6                NUMBER OF REPAIR LINES IN FLEET
NAV      STORAGE    120              MAXIMUM NUMBER ENGINES FOR 30 SHIPS
SHIPS    FUNCTION   XH$INT,L30       DELIVERY SCHEDULE FOR 30 SHIPS
1    2    3    4    5    6    8   12   16
7    8    9   10   11   12    4    4    4
13   14   15   16   17   18    8    4    4
19   20   21   22   23   24    4    4    4
25   26   27   28   29   30    4    4    4

         FUNCTION   RN2,C19          FUNCTION TO GENERATE TIME TO TBO
.009,066./.028,072./.047,078./.074,084./.120,090./.175,096./
.249,102./.342,108./.462,114./.582,120./.702,126./.804,132./
.878,138./.915,144./.944,150./.963,156./.982,162./.991,168./
1.000,174.
         GENERATE   FN$SHIPS,,,30    INTRODUCE 30 SHIPS PER SCHEDULE
         SAVEVALUE  INT+,K1,H
FIRST    MARK
         TEST E     N$FIRST,K1,HOP
         SPLIT      1,INFO           SEND SIGNAL TO START TIMING
         SPLIT      1,HOLD           DIVERT ONE TRANS. TO LOAD STOCK
HOP      MARK
         SPLIT      3,NEXT           CREATE FOUR ENGINE PER SHIP
NEXT     MARK
COUNT    MARK
FLEET    ENTER      NAV
         SAVEVALUE  OPER,FN1,H
         TRANSFER   ,XH$RAND,RNAV,RFAIL
RNAV     ADVANCE    ,XH$OPER         TIME TO FAIL F(TBO,OPSCHED)
JOIN     NAV
         LOGIC S    1
         ADVANCE    XH$TRANS         DELAY FOR TRANSPORTATION
         QUEUE      FAC              ARRIVE FOR REWORK
         ENTER      FAC
```

```
                     DEPART
                     ADVANCE     FAC
                     LEAVE       XH$REWOCK
LEARN    QUEUE       FAC
STOCK    GATE LS     POOL
         DEPART      1
         TEST E      V9,K1,OPEN
         LOGIC R     1
OPEN     MARK
         ADVANCE     XH$TRANS
         TRANSFER    ,FLEET
RFAIL    MARK
         ADVANCE     V$MEAN,V$MEAN      REPAIR TIME
         TRANSFER    ,JOIN
HOLD     MARK
         SPLIT       XH$LOAD1,STOC1
         ADVANCE     XH$TIME2
         SPLIT       XH$LOAD2,STOC1
         ADVANCE     XH$TIME3
         SPLIT       XH$LOAD3,STOC1
         ADVANCE     XH$TIME4
         SPLIT       XH$LOAD4,STOC1
         ADVANCE     XH$TIME5
         SPLIT       XH$LOAD5,STOC1
         ADVANCE     XH$TIME6
         SPLIT       XH$LOAD6,STOC1
         TERMINATE   0
STOC1    MARK
         TRANSFER    ,STOCK
INFO     MARK
         ASSIGN      7,1040
         SAVEVALUE   1+,K1
XXX1     MARK
         ADVANCE     1
         TEST L      S$NAV,N$COUNT,OUT   ENGINES NOW RFI
         LOOP        7,XXX1              REPLACE FAILED ENGS.
OUT      TRANSFER    ,FINAL
FINAL    MARK
         SAVEVALUE   INT,K1,H
         PRINT       1,2,Q
         PRINT       1,2,S
         TERMINATE   1
9        VARIABLE    N$COUNT-S$NAV
MEAN     VARIABLE    XH$OPER/2
1        START       1,NP
         END
```

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```
*****
*   *****
*   *       FORTRAN ANALYTICAL MODEL COMPUTER PROGRAM
*   *
*   *****   COMPUTER PROGRAM FOR THE CALCULATION OF THE SYSTEM PREFORMANCE
C           MEASURES FOR THE LM-2500 USE/ REWORK CYCLE.
C           THE MODEL USES THE METHOD DEVELOPED BY KOENIGSBERG IN 1960.
C           THE PROGRAM SOLVES PROBLEMS WHERE N-A >= M.
C&  9  N ADDITION THE PROGRAM IS DESIGNED FOR USE AS AN INTERACTIVE
C           TIME SHARE SYSTEM.
C
      IMPLICIT REAL*8 (A,B,C,D,S,U,H)
      INTEGER Z(6)
      DIMENSION A(1000),SP(1000)
      CALL ERRSET(208,256,-1,1,0)
1111  CONTINUE
C
C     READ THE INPUTS
C
      CALL IXCLOK (Z)
      WRITE(6,9100)Z(1),Z(2)
9100  FORMAT(':0','DATE ',2A4,//,' DETERMINATION OF SYSTEM PERFORMANCE
     1MEASURES OF LM 2500 USE/REWORK CYCLE.',//,' AFTER EACH PARAMETER E
     2XAMPLE, ENTER YOUR PARAMETER CHOICE IN THE FORMAT SHOWN.')
      WRITE(6,9101)
9101  FORMAT(':0','1.   NUMBER OF SHIPS',/,' EXAMPLE 30   (YOU ENTER NUMBER
     1  XX AND HIT RETURN)')
      READ(5,9102)KS
9102  FORMAT(I2)
      WRITE(6,9103)
9103  FORMAT(':0','2.   NUMBER OF ENGINES PER SHIP',/,' EXAMPLE 4   (X)')
      READ(5,9104)KE
9104  FORMAT(I1)
      WRITE(6,9105)
9105  FORMAT(':0','3.   NUMBER OF SPARE ENGINES',/,' EXAMPLE 20   (XX)')
      READ(5,9102)KP
      WRITE(6,9108)
9108  FORMAT(':0','4.   NUMBER OF REPAIR LINES',/,' EXAMPLE 06   (XX)')
      READ(5,9102)M
      WRITE(6,9109)
9109  FORMAT(':0','5.   AVERAGE REWORK TIME PER ENGINE (WEEKS)',/,' EXAMPL
     1E 5   (X)')
      READ(5,9210)KTRW
9210  FORMAT(I1)
      WRITE(6,9106)
9106  FORMAT(':0','6.   TBO (TIME BETWEEN OVERHAULS, HOURS)',/,' EXAMPLE 4
1000  (XXXX)')
```

```fortran
9107  READ(5,9107)KTBO
      FORMAT(I4)
      WRITE(6,9211)
9211  FORMAT('0','7.   ENGINE OPERATING HOURS PER YEAR',/,'  EXAMPLE 2000
     1 (XXXX)')
      READ(5,9107)KTOR
      WRITE(6,9212)KS,KE,KP,M,KTRW,KTBO,KTOR
9212  FORMAT('0','CHECK YOUR PARAMETER CHOICES',//,' NUMBER OF SHIPS',I1
     17,/,' NUMBER OF ENGINES/SHIP',I10,/,' NUMBER OF SPARES',I16,/,' NU
     2MBER OF REPAIR LINES',I10,/,' AVERAGE REWORK TIME',I13,/,' TBO',I
     329,/,' ENGINE OPERATING HOURS',I10,//,' ARE THESE CORRECT?   IF YE
     4S  TYPE 1',/,' IF NO TYPE 0, PROGRAM WILL RESTART')
      READ(5,9104)KT
      IF(KT.EQ.0)GO TO 1111
C
C     CHANGE THE INPUTS TO THE PARAMETERS USED BY THE MODEL.
C
      TRW=KTRW
      TBO=KTBO
      TOR=KTOR
      KA= KS * KE
      N= KA + KP
      FAILR= 1.0 / (( TBO/ TOR) * 52.0 * 0.9)
      REPR= 1.0 / TRW
      L= N+1
      NA= N-KA
      RHO= FAILR / REPR
      ARHO= KA * RHO
C
C     CALCULATE THE P(I)
C
      A(I)= 1.0
      MP= M + 1
      I= 2
C
C     I<M
C
1000  IF(I.GT.MP) GO TO 2000
      IM= I - 1
      A(I)= A(IM) * ARHO / IM
      I= I+1
      GO TO 1000
C
C     M<= I <=NA
C
2000  NAP= NA + 1
      IF(I.GT.NAP) GO TO 3000
      IM= I - 1
```

```fortran
      A(I)= A(IM) * ARHO / M
      I= I+1
      GO TO 2000
C
C
      NA<= I <= N
C
 3000 IF(I.GT.L) GO TO 4000
      IM= I - 1
      A(I)= A(IM) * RHO * (N+2-I) / M
      I= I+1
      GO TO 3000
C
 4000 DENOM= 0.0
      DO 4500 I= 1,L
      DENOM= DENOM + A(I)
 4500 CONTINUE
      DO 4600 I= 1,L
      SP(I)= A(I) / DENOM
 4600 CONTINUE
      STOT= 0.0
      DO 5000 I=1,L
      STOT= STOT + SP(I)
 5000 CONTINUE
      ACC= DABS( 1.0 - STOT)
      IF(ACC.GT.0.001)GO TO 5500
      GO TO 5700
 5500 WRITE(6,5600)STOT
 5600 FORMAT('0',' WARNING ** POSSIBLE LOSS OF ACCURACY',/,' THE SUM OF
     1THE STATE PROBABILITIES IS',D25.15,//)
 5700 CONTINUE
C
C     CALCULATE THE SYSTEM PREFORMANCE MEASURES.
C
      BARN1=0.0
      DO 6000 I=1,N
      IP= I + 1
      BARN1= BARN1 + (I *SP(IP))
 6000 CONTINUE
C
C     BARN2= N - BARN1
C
      BARW1= 0.0
      MM=M+ 1
      DO 6100 I= MM,N
      IP= I + 1
      BARW1= BARW1 + ((I-M) *SP(IP))
 6100 CONTINUE
```

```
C
        BARW2= NA * SP(1)
        DO 6200 I=1,NA
        IP= I + 1
        BARW2= BARW2 + ((NA-I) *SP(IP))
6200    CONTINUE
C
        H1= BARN1 - BARW1
        H2= BARN2 - BARW2
        H2S= KA - H2
C
        D1=0.0
        DO 6300 I=M,N
        IP= I + 1
        D1= D1 + SP(IP)
6300    CONTINUE
        D1= D1 * 100.0
C
        D2= SP(1)
        DO 6400 I=1,NA
        IP= I + 1
        D2= D2 + SP(IP)
6400    CONTINUE
C
C
        UM= H1 / M
        UM= UM * 100.0
        UN= H2 / N
        UN= UN* 100.0
C
        DLA= FAILR * KA * D2
        NAPP= NA + 2
        DO 7000 I=NAPP,N
        DLA= DLA + (FAILR * SP(I) * (L-I))
7000    CONTINUE
        DCYCL= N / DLA
C
C       PRINT THE OUTPUT
C
        WRITE(6,9800)
9800    FORMAT('0',///,' LM 2500 USE/REWORK SYSTEM PREFORMANCE MEASURES',/
       1/)
        WRITE(6,9801)BARW1,H1,UM,D1
9801    FORMAT('0',"REWORK FACILITY STATISTICS',//,' AVERAGE NUMBER OF ENG
       1INES AWAITING REWORK',F9.1,/,' AVERAGE NUMBER OF ENGINES BEING REW
       2ORKED',F10.1,/,' AVERAGE % CAPACITY USED',F27.1,/,' %TIME ALL REP
       3AIR LINES BUSY',F22.1)
        WRITE(6,9802)H2,H2S,BARW2,UN,DCYCL
```

```
9802 FORMAT('0',;'FLEET/POOL STATISTICS',//,' AVERAGE NUMBER OF ENGINES
     1IN FLEET',F16.1,/,' AVERAGE NUMBER OF ENGINES SHORT IN FLEET',F10.
     21,/,' AVERAGE NUMBER OF ENGINES READY FOR ISSUE',F9.1,/,' AVERAGE
     3% ENGINES OPERATIONAL',F21.1,/,' AVERAGE CYCLE TIME (WEEKS)',F24.1
     4)
     IS= 1
     DMIS= (1.0 - D2) * 100.0
     WRITE(6;9803)IS,DMIS
9803 FORMAT('0',;'% TIME FLEET IS SHORT',I4,'  OR MORE ENGINES',F8.1)
7300 IF(DMIS.LT.30.0)GO TO 7400
     SPS= 0.0
     DO 750J I=1,5
     NAA= IS + I+NA
     SPS=SPS + SP(NAA)
7500 CONTINUE
     SPSP= SPS * 100.0
     IS= IS +5
     DMIS= DMIS - SPSP
     WRITE(6;9804)IS,DMIS
9804 FORMAT(' ',I25,F25.1)
     GO TO 7300
7400 CONTINUE
     WRITE(6;9805)
9805 FORMAT('0';"DO YOU DESIRE TO RUN ANOTHER SET OF PARAMETERS?",/,'
     1IF YES, TYPE 1;  IF NO, TYPE 0')
     READ(5;9104)KT
     IF(KT.EQ.1) GO TO 1111
     STOP
     END
```

LIST OF REFERENCES

1. Cushing, J.S., Gautier, W. K., and Long, D. A., _A Simulation Study of the LM-2500 Gas Turbine Engine Inventory System_, M.S. Thesis, Naval Postgraduate School, Monterey, California, March 1972.

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